

Satellite-Derived Tropical Cyclone Intensities and Structure Change (TCS-08 and ITOP)

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LONG-TERM GOALS

To understand tropical cyclone (TC) structure and the time evolution from genesis to a mature storm while focusing on environmental conditions that impact rainband and inner core changes that are directly related to a TC's intensity and resultant wind and rain fields.

OBJECTIVES

Develop accurate automated satellite-based techniques to estimate TC intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, and strengths ranging from tropical depression to Category 5). Create products that enable the TC community to monitor the three dimensional (3-D) TC environment (winds, moisture, and sea surface temperatures) and advance our ability to forecast TC intensity changes with a special emphasis on western Pacific (WPAC) typhoons.

APPROACH

Satellite sensors represent the only observing platform that can currently provide the geographic coverage, and spatial, spectral, and temporal sampling required to monitor TC parameters in a near real-time mode. This project will focus on developing new satellite-based tools that assist the TC community in understanding TC structure changes by incorporating coincident recon data sets that can verify the fidelity of the satellite product suite, especially in the data poor (recon) WPAC region (Hawkins and Velden, 2011, Hawkins et al., 2010a, and Global Perspectives on Tropical Cyclones, 2009, Hawkins et al, 2009).

The Tropical Cyclone Structure (TCS-08, Harr et al, 2009) and Impact of Typhoons on the Ocean by Typhoons (ITOP - 2010) field programs provided unique aircraft reconnaissance (recon) data sets that will be used to validate a suite of satellite-based capabilities; a) TC intensity estimates, b) monitoring the time evolution of the 3-D environmental structure within and around TCs, and c) determining the inherent limitations of each method and potential way forward.

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While Atlantic recon data has provided the only data to formulate these algorithms, WPAC data is sorely needed due to specific differences between TCs in both basins. Air Force WC-130J penetrations of the TC eye during TCS-08 and ITOP will be a key focus by incorporating dropsondes, Stepped Frequency Microwave Radiometer (SFMR) surface wind speeds, and flight level winds. The WC-130J derived minimum sea-level pressure (MSLP) and maximum sustained winds (Vmax) will form the basis for enhanced best-track values used to validate all satellite-derived intensity values.

Automated Dvorak Technique (ADT) intensities using IR data have been used operationally for multiple years, but suffer when a central dense overcast obscures vital storm structure (Hawkins and Velden, 2008). Microwave imagers, which can “see through” non-raining clouds, thus monitoring eyewall genesis, will be tested to see if they can add value to the ADT intensities until a clear eye permits the ADT to apply Dvorak “eye” rules. Our team will include the Cooperative Institute for Meteorological Satellite Studies (CIMSS, Chris Velden’s group) who have created the original ADT algorithms under NRL sponsorship and incorporated microwave eyewall structure information.

WORK COMPLETED

1. Validate ADT, AMSU and SATCON TC intensities with final TCS-08 QC’d storm intensity database and intercompare with Atlantic-based results.
2. Derive a microwave imagery only TC intensity module for inclusion in the satellite consensus (SATCON) estimate.
3. Create 1st SSMIS warm core anomaly intensity algorithm based on previous AMSU methodology using 2008-2009 recon data in Atlantic and Pacific.
4. Utilize QC’d dropsonde data sets to investigate select cases illustrating dry air intrusion into the system’s inner core and match with coincident MIMIC TPW static and animation data sets.
5. Use both H*Wind and manual surface wind field analyses to create and monitor TC wind field structure and monitor asymmetries and temporal structure changes.
6. Participate in ITOP field program via both near real-time satellite product support and as WC-130J mission scientist based in Guam.

TECHNICAL RESULTS

Section 1: Tropical Cyclone Intensity Validation Data Set

2008 was an anomalous year with a distinct lack of westerly winds in the deep tropics during July, August and some of September. The WC-130J was able to sample typhoons Sinlaku (11 fixes) and Jangmi (8 fixes), while the NRL P-3 also sampled Hagupit. Each flight pattern was designed to coincide with Advanced Microwave Sounding Unit (AMSU) overpasses by calculating upcoming AMSU passes and storm center coverage. Professor Russ Elsberry (Naval Postgraduate School) led a “best track” team that created TC estimates for all date/times of AMSU overflights by reviewing all WC-130J recon fix data sets, SFMR ocean surface wind speeds, dropsonde boundary layer and surface winds, QuikSCAT and ASCAT scatterometer surface wind vectors and all ship/buoy reports.

Table 1 summarizes the results using 14 AMSU overpasses deemed good enough in terms of sensor swath position and coincident within +/- 3 hours of WC-130J derived center fixes. Blind Dvorak are values from an expert satellite analysis team who used manual Dvorak after the fact while not looking at any other data sets, “Oper Dvorak” is the consensus of Dvorak estimates from all western pacific operational agencies, “w/JMA Koba adj” incorporates the Japan Meteorological Agency’s (JMA) wind pressure relationship, ADT are the ADR-IR values, and ADT w/MW are the ADT with microwave imager adjustments. Note the reduced absolute error (abs error) and root mean square error (RMSE) derived with the ADT w/MW versus the standard ADT method. In addition, the microwave adjusted ADT are better than the operational Dvorak, but not the “blind” Dvorak, illustrating how experts with 30+ years experience can outperform within this very limited sample. The sample size means these results are NOT statistically significant and further WPAC TC penetrations are sorely needed.

The TCS-08 data base was effectively doubled during ITOP, as the aircraft recon focused on three long lived typhoons: 1) Malakis, 2) Fanapi, and c) Megi. All three TCs developed near Guam and thus provided extended opportunities for aircraft flight patterns to sample both the inner core and surrounding wind field structure. Our team tentatively estimates 20 AMSU overpasses that are coincident (+/- 3 hours) with WC-130J vortex messages. A “best track” is currently being assembled and then intercomparisons with the various satellite intensity estimates will be evaluated, including Cat 5 values for Typhoon Megi.

Section 2: Microwave Imager Data Utilization in TC Intensity Estimates

A satellite-based automated technique that takes advantage of a microwave imager’s capability to “see through non-raining clouds” and map eyewall formation has been transitioned to a SPAWAR PMW-120 work unit. The ADT-microwave (ADT-MW) algorithm incorporates eyewall structure data only seen routinely via microwave imager channels and uses thresholds to determine when IR-based ADT values should be adjusted higher (Sears et al, 2010). Central dense overcast (CDO) conditions typically are associated with ADT estimates that are biased low and represent perfect scenarios where the additional eyewall details from microwave data enable a revised intensity estimate closer to aircraft measured maximum sustained winds and minimum sea level pressure (MSLP). Microwave imager data is also being studied to determine if precursors to rapid intensification (RI) are contained within the rainband organization only seen in this unique data set (Velden et al., 2010) while using new automated center finding algorithms (Wimmers and Velden, 2010).

In addition, our team has made progress on extracting TC intensity values from passive microwave imager digital data sets. A machine learning algorithm has been developed that incorporates TC features mainly based on ice scattering (85 GHz) brightness temperature (Tb) digital data from the Special Sensor Microwave Imager (SSM/I). Derived products such as polarization corrected temperature (PCT), rainrate, and total precipitable water (TPW) were included while validating against Atlantic-basin aircraft reconnaissance vortex penetrations. Figure 2 summarizes the results that include efforts to isolate any cases where systematic biases and problems may be causing difficulties.

As expected from preliminary visual inspection and long term data analysis, TCs experiencing high shear have distorted 85 GHz signatures that only human inspection can effectively recognize and attempt to compensate the TC intensity estimates. Figure 3 show cases a high shear case as well as an example when chaotic central core convection and multiple eyewalls present problems to the current microwave intensity algorithm. The RMSE is reduced from ~ 16 kts to 14 kts when both the high

shear and convection near the center cases are removed from the data set. Several methods are available to detect high shear cases, using independent low-high level wind estimates as well as comparing center finding algorithms with convective clusters.

Our microwave intensity technique is now focusing on additional “features” available from using 37 GHz data that details lower-level cloud liquid water and is less affected by shear aloft and convection near the center. However, the question is whether the significantly reduced spatial resolution (~ 13 km versus 30 km) will provide sufficient detail to map features that are uniquely associated with storm intensity. These results were presented at the American Meteorological Society’s 17th Satellite Meteorology and Oceanography Conference in Annapolis, MD (Bankert and Hawkins, 2010).

Section 3: Create SSMIS TC Intensity Algorithm

SSMIS calibration and validation efforts have taken considerably longer than expected due to a suite of satellite sensor issues that precluded using the data until recently. Anomalous reflector emissions were dominated by Earth and spacecraft shadowing, introducing 1.5-2 K jumps at 50-60 GHz and 5-7 K at 183 GHz. In addition, F-16 had solar intrusions into the warm reference load that resulted in errors of 1-1.5 K, but this was corrected in F-17 by adding a “fence” to keep out direct solar rays. Additional issues were discovered, but the bottom line was the cal/val team spent several years characterizing the source of each brightness temperature (Tb) error and then developing a ground software mitigation processing solution. The F-16, F-17 and now F-18 SSMIS sensors are now available for study and our team will evaluate how the SSMIS frequencies stack up with AMSU for the purposes of mapping warm core temperature anomalies above TCs that are in turn highly correlated with TC intensity.

Section 4: Dry Air Intrusion Mapping via Satellite Remote Sensing

The “moisture environment” within which a TC is embedded and/or moves into is crucial in determining whether the system can tap into a moisture rich atmosphere/ocean zone or whether it is inhibited due to environmental “constraints”. The TC community is much more familiar with the well documented dry air impacts for Atlantic and East Pacific systems due to the prevalence of frequent Saharan Air Layer (SAL) events and dry environmental air to the north respectively. In the WPAC, dry air can be created by 1) outflow from nearby TCs whose descending air warms and dries, 2) mid-latitude intrusions that dip southward due to a combination of synoptic and mesoscale conditions, and 3) occasional continental air from SW Asia under favorable atmospheric flow. Monitoring dry air can be accomplished by using both microwave imagers and sounders to retrieve total precipitable water (TPW) and these products are now routinely created and distributed via the web by both (NRL, static basin wide composites: <http://www.nrlmry.navy.mil/tropics-bin/tropics.cgi>) or animations using a temporal morphing technique to provide a seamless TPW loop. (CIMSS: <http://cimss.ssec.wisc.edu/tropic/real-time/tpw2/global/main.html>).

TPW represents the total precipitable water available within a unit column of air from the top of the atmosphere to the ocean surface. The vast majority of the water vapor exists within the lower troposphere, thus if substantial dry air is revealed in TPW products, it most likely reaches down to low levels that may impede TC storm thermodynamics. Figures 3 and 4 reveal some of the limitations of using satellite derived TPW using a case from TCS-08 when coincident aircraft dropsonde data enabled a closer look at the 3-D moisture structure. The SSMIS TPW in Fig. 3 depicts a relatively

moist environment around TCS-025 with some modest or lower values to the north (~ 50-55mm). Coincident WC-130J dropsonde relative humidities at 400 mb and 700 mb (Fig. 4) permit the analyst to monitor the 3-D moisture structure: a) very dry RH values aloft (20%) and to the north, associated with cooler dry air being advected in from mid-latitudes and corresponding with strong shear, b) modestly dry air (60%) at 700 mb coming down from the north, and thus c) disagreement between the dropsonde RH values and SSMIS TPW observations.

In summary, TPW is driven by the vast moisture values in the lowest tropospheric levels and thus can be misleading or unable to capture real 3-D moisture gradients within the TC domain. Aircraft dropsonde data are thus crucial in adequately monitoring the TC environment and detailing moisture layers and potential dry air intrusions that signal ongoing structure changes that need to be factored into TC analyses. These results would not have been available without flying high altitude square spirals in concert with ~ 30 dropsondes centered on mid-level vortex.

Section 5: Wind Field Analyses

Creating reliable ocean surface wind fields for TCs is problematic, even in the Atlantic where there's an abundance of operational and research recon flights. To inter-compare surface wind fields of varying datasets, this research was limited to two case studies: Typhoon Jangmi and Typhoon Sinlaku. Both cases were flown by four research aircraft: P-3 (NRL), WC-130 (USAF), Taiwan's DOTSTAR, and the German Falcon (DLR). In all instances, flight level data as well as dropsonde profiles were available as well as the WC-130J-based SFMR. Ocean surface wind vectors from QuikSCAT, ASCAT, and WindSat were utilized when coincident with analysis times. Of particular interest, analysis of Sinlaku was favored due to the existing NRL NOPP-TC dataset. Post-processing of scatterometry data from multiple sources allows a standard comparison of both data processing and analysis schemes, in addition to comparison between observing platforms. The NOPP-TC dataset includes: UCF QuikSCAT, BYU QuikSCAT, EUMETSAT ASCAT, NOAA SSMI, NOAA SSMIS, NRL WindSat, and NOAA WindSat.

Ship and METAR observations were additionally available from NOAA HRD. Data from CIRA multiplatform analysis, courtesy of John Knaff, (http://rammb.cira.colostate.edu/products/mtc_swa/) were available for comparison and input into analysis schemes. Finally, cloud tracked MTSAT low-level winds from CIMSS were incorporated.

Two surface wind analysis schemes were considered: a) the H*Wind surface method (Powell et al 1998), from NOAA HRD, provides research and near-operational products of TC surface wind, but with limited flexibility and b) the Spline Analysis at Mesoscale Utilizing Radar and Aircraft Instrumentation (SAMURAI) created by Michael Bell (2010) of the Naval Postgraduate School that places an emphasis on customization and utility in TC analyses. While H*wind has been used for near real-time applications for multiple years, SAMURAI is in development stage as was not available for full testing due to Dr. Bell's heavy PREDICT schedule. Thus, this summary focuses on results after extensive testing with H*Wind.

Figure 5 demonstrates the tendency of H*Wind to inflate the wind field radii. Perhaps due to the coarse nature of the output grid (and the narrow radial gradient of wind speeds), H*Wind over analyzes its own objective grid and expands the wind field with each analysis iteration. In addition, settings and weights for incorporating a background field and gridded field with the observed data

produce inconsistent results. The above occurrences suggest that H*Wind is more of a 'black box' tool than a customizable method for surface analysis. However, some hopeful results were also obtained. Although not shown here, a comparison of H*wind grids using buoy directions versus some analyses without show that the directional bias in the velocity fields are on the order of 5-10 degrees. This indicates that the level of error associated with the analysis routine and the observations is on par with changes using surface buoy data. Such results are preliminary and should be explored with further methods.

Figure 6 demonstrates a sample SAMURAI analysis of UCF QuikSCAT for Sinlaku. In addition to a variety of customizable methods of analysis, one benefit shown in the figure is the ability to resolve mesoscale minima and maxima wind fields (as opposed to H*Wind's propensity to only resolve one radius of maximum winds and an emphasis wavenumbers 0, 1, and 2). Dr. Bell is continuing to refine SAMURAI and also build a graphical user interface (GUI) that will enable other researchers to more readily incorporate this technique for their own unique studies, but early results are promising.

3-D wind field structure knowledge is crucial when evaluating TC intensity trends and is especially needed for genesis cases. Thus, TCS-08 and ITOP included what are called "high altitude invest" flight patterns where the WC-130Js fly as high as possible (27,000-31,000') and utilize expendable probes (dropsondes and airborne expendable bathythermographs, AXBTs) to sample both the atmospheric and ocean structure (Hawkins et al, 2010b). A square spiral pattern with dimensions of 4-5 degrees on a side is centered on the mid-level vortex and incorporates ~ 30 dropsondes and 20-30 AXBTs to map the 3-D wind, thermal and moisture field down to the surface and then the ocean thermal structure down to 1000-1500 m. These continuous measurements provide details not feasible via any other sensor suite.

Figure 7 highlights the advantages in genesis studies afforded by the high altitude invests. Invests are typically flown at low-levels (1500') in order to a) sample the system's maximum sustained winds (usually near this level), and b) use these flight level winds to better vector the plane into the "low-level" center, and thus c) determine if there is indeed a closed circulation. However, the price paid to fly at 1,500' is the simple fact no information > 1,500' is obtained. Figure 7 reveals how much crucial wind information is possible via high altitude dropsonde data sets and illustrate that this TCS-08 genesis case represented a high wind shear event with substantial displacement between the low and mid-level vortex. High level wind shear was tilting the vortex over and helping bring in drier air, both detrimental to genesis or system intensification. Thus, vital 3-D data would have been unavailable if standard low-level invest data sets had been gathered.

Section 6: ITOP Field Mission Support

NRL's Satellite Meteorological Applications Section (7541) provided a unique suite of near real-time products geared toward ITOP field mission support. The NRL TC web page was tailored to the ITOP foci and the mission operations centers in Monterey, CA and Guam were able to "drive, activate, adjust" the web products via simple email messages. In particular, the NRL ITOP web page's inclusion of microwave imagers/sounders permitted ITOP analysts to better comprehend genesis system convective organization as well as understand typhoon inner core structure that was crucial in planning locations for aircraft deployable buoys in front of typhoon's Malakis, Fanapi, and Megi. Figure 8 is an example of a special sea surface temperature (SST) product using the Advanced

Microwave Scanning Radiometer (AMSR-E) that NRL distributed in near real-time to assist in monitoring TC induced cold wakes.

<http://www.nrlmry.navy.mil/ITOP.html>

Thirty three (33) invests or interesting areas of convective activity were sampled during ITOP from August to September and include a large number of potential genesis cases as well as the three typhoons that became the main focus of ITOP's ocean response theme. Thus, storm structure was captured via multiple satellite sensors from beginning to end.

In addition, the PI participated as a WC-130J mission scientist, spending close to three weeks guiding flights into ITOP invest systems and working with the Air Force weather officers, crew and the operations centers to gather the optimum set of recon data (dropsondes, AXBTs, flight level, SFMR, and radar recordings) for both real-time and later scientific research efforts.

IMPACT/APPLICATIONS

The TCS-08 and ITOP (2010) field programs have provided valuable in-situ and remote sensing data set that will assist our satellite validation efforts on multiple fronts (TC intensity, surface wind fields, dry air intrusions, and storm shear). Our team has made progress on multiple fronts, benefiting associated 6.4 work units that will carry new TC intensity algorithms to near real-time support and providing JTWC and the TC community with new insight on WPAC storm structure.

TRANSITIONS

The ADT-MW module was transitioned to a PMW-120 6.4 project and was used this past summer season by both the National Hurricane Center and the Joint Typhoon Warning Center (JTWC) for near real-time guidance. The microwave center finding method is now in 6.4 and being transitioned to NOAA.

TCS-08 field program lessons learned greatly aided the ONR sponsored Impacts of Typhoons On the Pacific (ITOP) operations. The ITOP near real-time SST products, especially the microwave SST suite, were found to assist the analysts understand the complex ocean response to storm induced upwelling and will assist in future TC monitoring in a region previously thought to be relatively "benign" when it comes to ocean fronts and eddies and ocean heat content that can impact future storm intensity.

RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the Program Executive Office for C4I&Space/PMW-120 entitled "Tropical cyclone intensity and structure via multi-sensor combinations", funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC and the National Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC and the TC research community has been extremely positive in recent technical conferences.

This project works closely with JTWC/NHC and FNMOC to understand the needs of the operational TC community via routine emails, phone calls and technical conferences (AMS, IHC, and TCC). Feedback is routinely solicited from all operational partners in order to understand how the 6.2 efforts outlined here can best be aligned to answer real world requirements and needs.

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Table 1: List of TCS-08 validated satellite intensity estimates using 14 AMSU overpasses compared to best track intensities incorporating WC-130J dropsondes, SFMR, and flight level winds with all other routine data sets showing the ADT-MW are superior to ADT values in this limited data set.

N=14	Oper Dvorak Consensus (w/Koba)	ADT w/MW	CIMSS AMSU	SATCON
Bias	0.1	-1.0	-1.9	-1.3
Abs Error	7.5	10.7	4.9	6.0
RMSE	8.9	12.8	6.3	7.2

RMSE (kts)

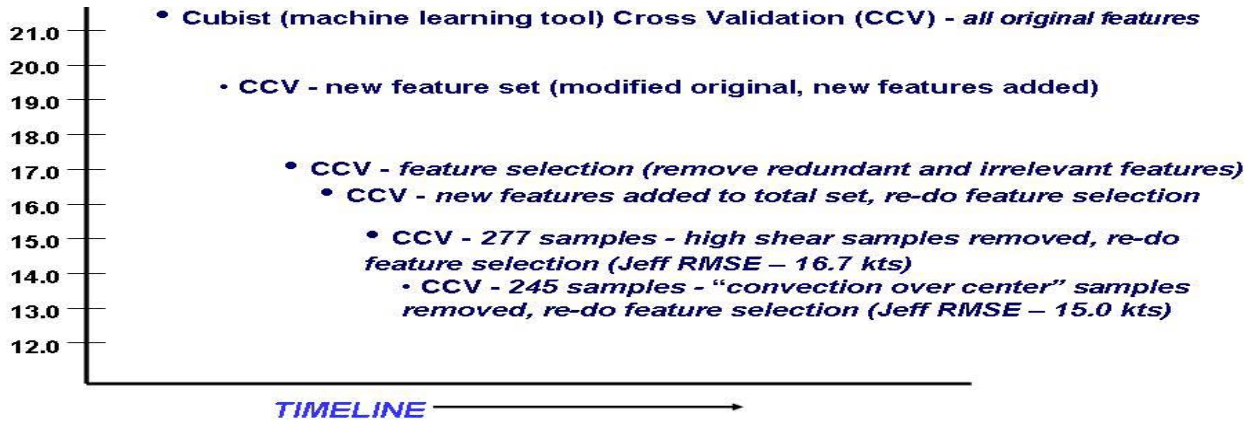


Figure 1: The root mean square error (RMSE) in wind speed (kts) for the microwave imager based TC intensity algorithm when applied to a ten year Atlantic recon centered data set with ~ 319 members

SSM/I 85 GHz images (BT)

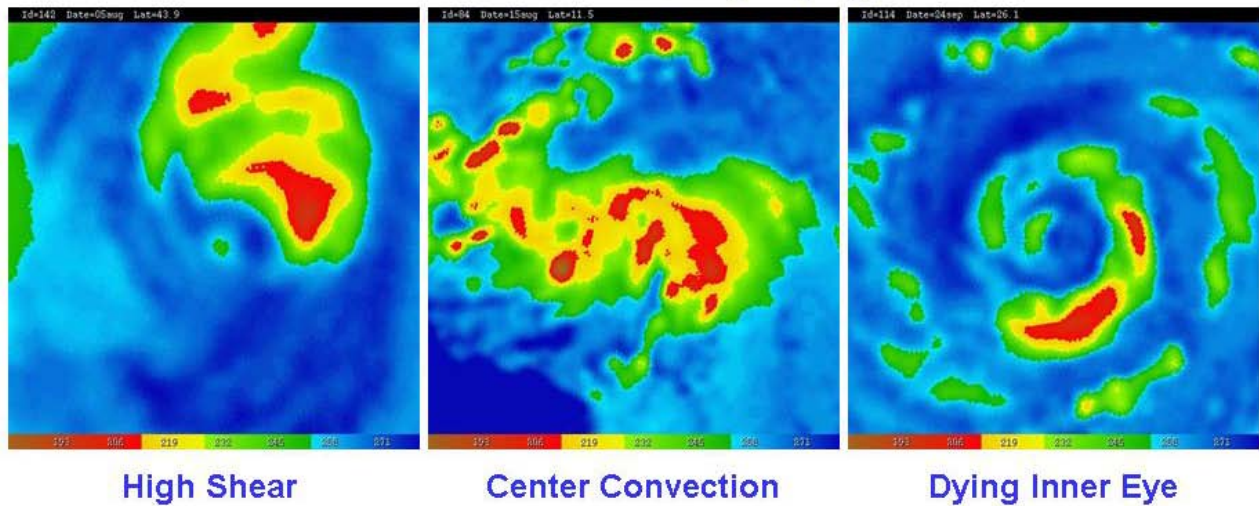


Figure 2: 85 GHz SSM/I brightness temperature imagery for three scenarios that can cause problems for the automated microwave imager intensity algorithm; 1) high shear, 2) disorganized convection near storm center, and 3) multiple eyewalls, especially when the inner eye is decaying.

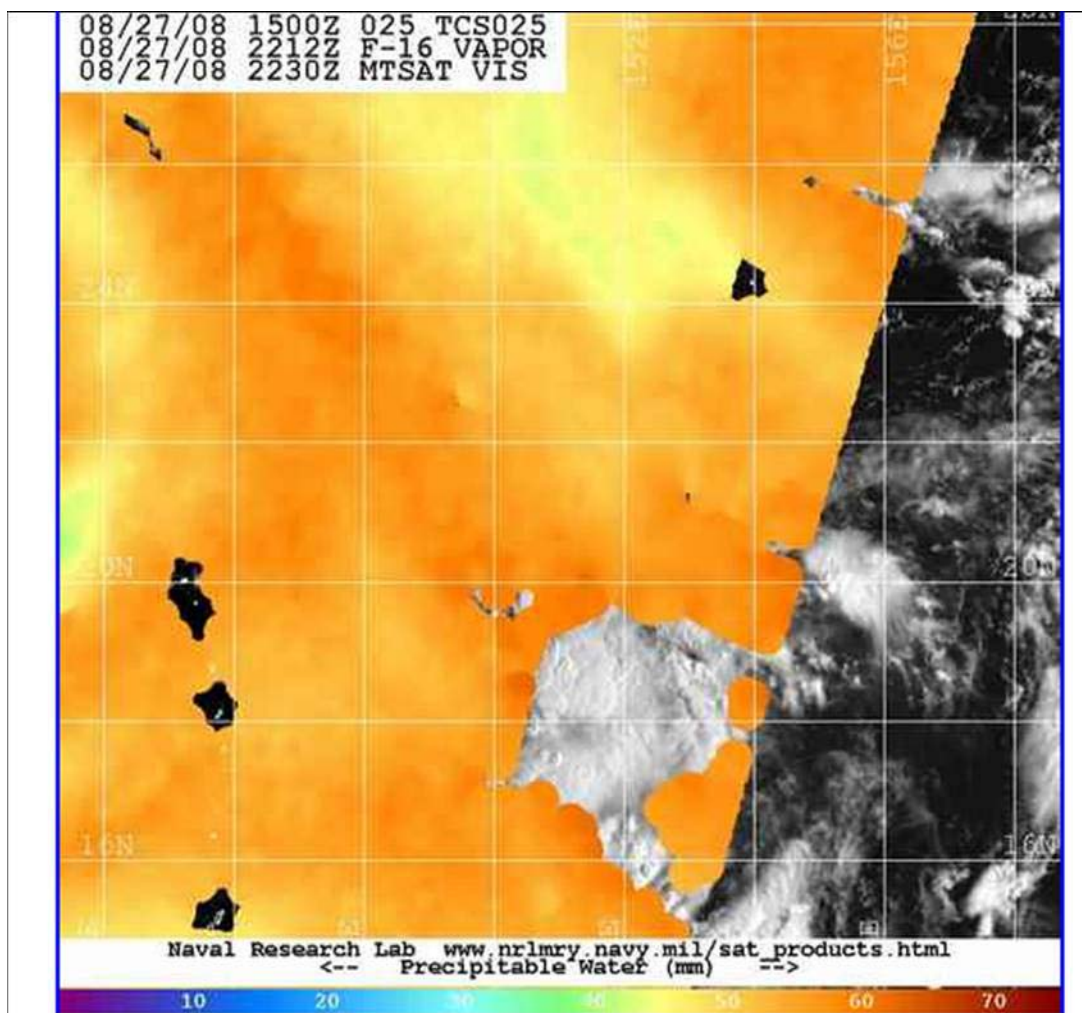


Figure 3: Total precipitable water (TPW) for TCS-025 on August 27, 2008 at 2212Z as viewed by the F-16 SSMIS sensor while the system was just northeast of Guam (note 2x2 deg latitude and longitude grid). Note TPW values are moderately high everywhere (50-70 mm) with some evidence of lower TPW on the north side.

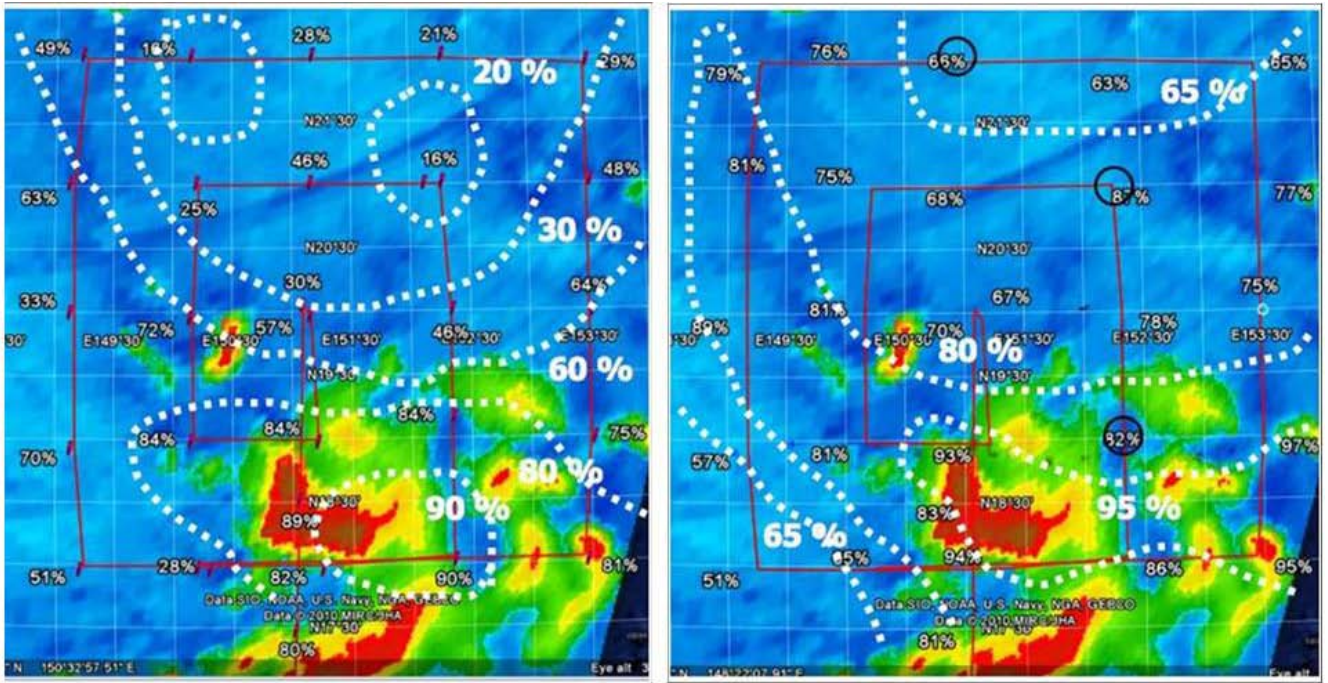


Figure 4: 91 GHz background image depicts the mesoscale convective activity (yellow and red colors represent significant rain areas) associated with a disorganized TCS-025. Overlain on top are WC-130J dropsonde derived relative humidity values (400 mb on the left, 700 mb on the right) within the square spiral flight pattern centered on the mid-level vortex. Note the drastic change in moisture from the upper to lower levels. This moisture information is not present in the satellite derived TPW data in Fig. 3.

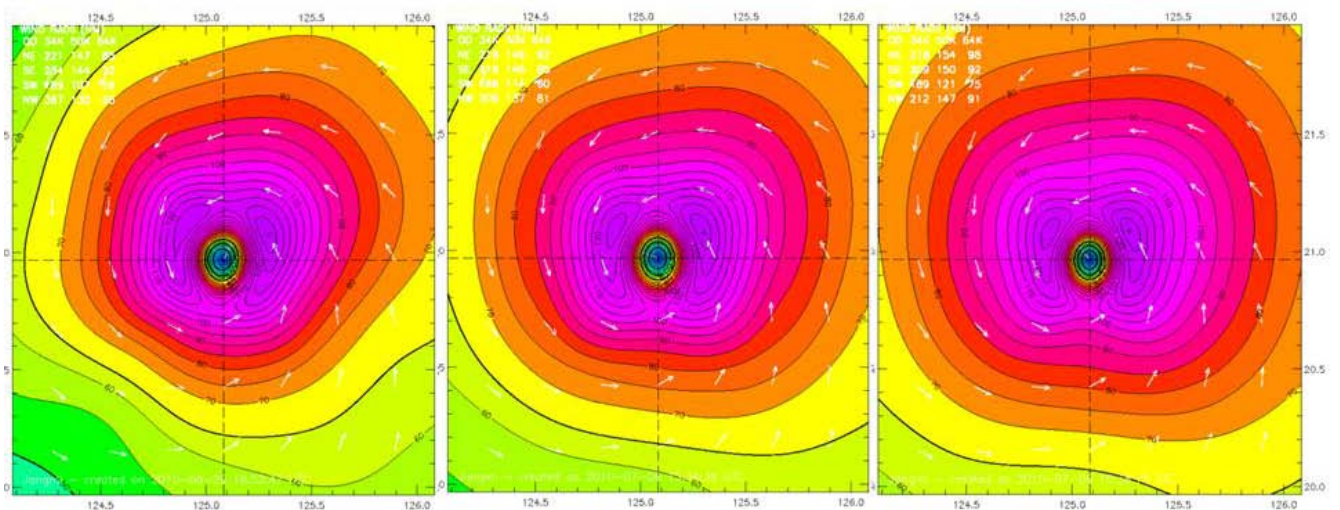


Figure 5: Left frame: H*Wind ocean surface wind field analyses for Super Typhoon Jangmi on Sept. 27, 2008 at 0755Z using SFMR, QuikSCAT, Dropsonde, METAR, and ship observations. Middle frame: use H*Wind grid values from left frame and reanalyze, right frame, iterate on middle frame's grid field values. Storm wind field expands unrealistically.

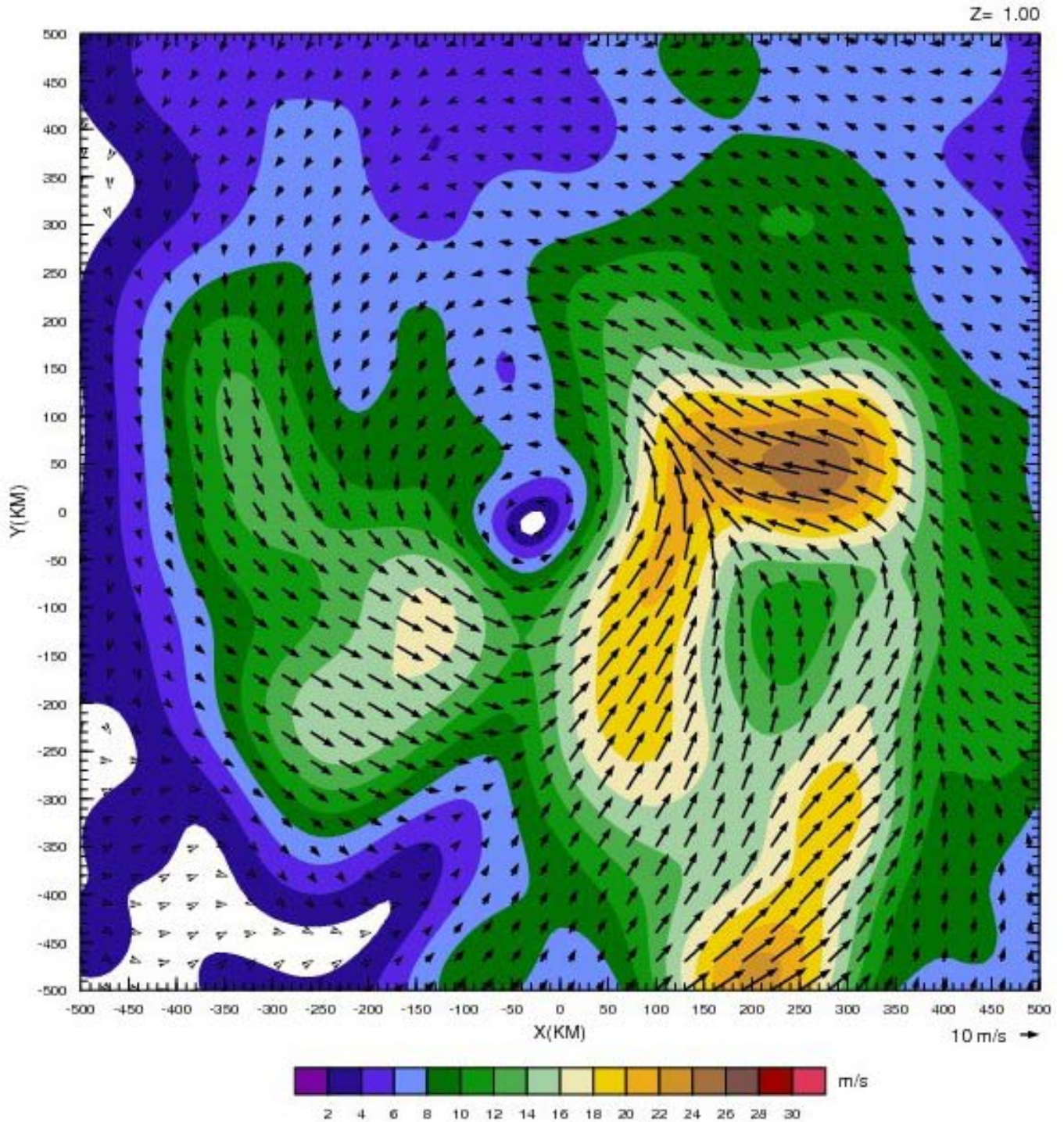


Figure 6: Surface wind vector analysis (m/s) using Michael Bell's SAMURAI analysis scheme and UCF high resolution QuikSCAT ocean surface wind vectors for Typhoon Sinlaku. The analysis is able to capture TC wind field asymmetries not readily handled by H*Wind and other methods.

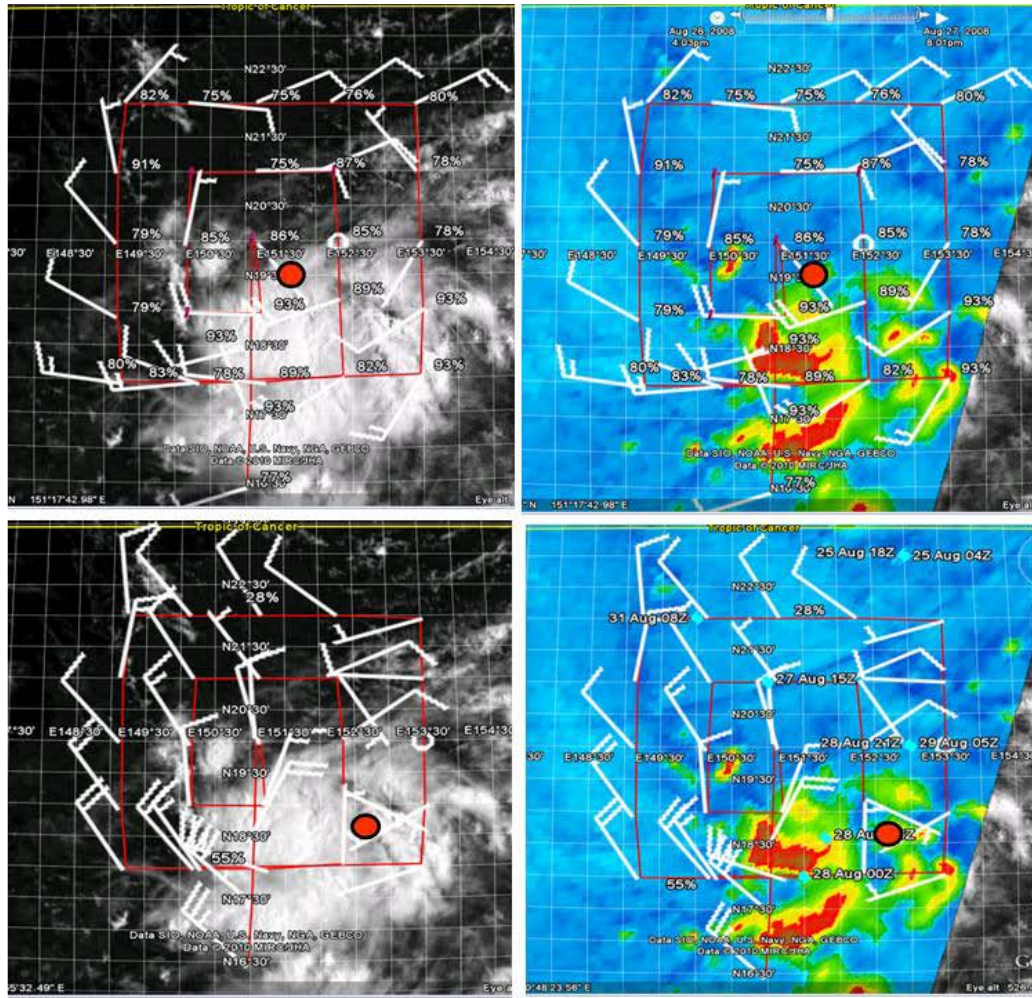


Figure 7: Dropsonde derived surface winds (top frame) and 400 mb winds (bottom row) overlain on coincident MTSAT visible and SSMIS 91 GHz brightness temperatures. Note the dramatic shift in wind centers from the surface to 400 mb due to very strong shear.

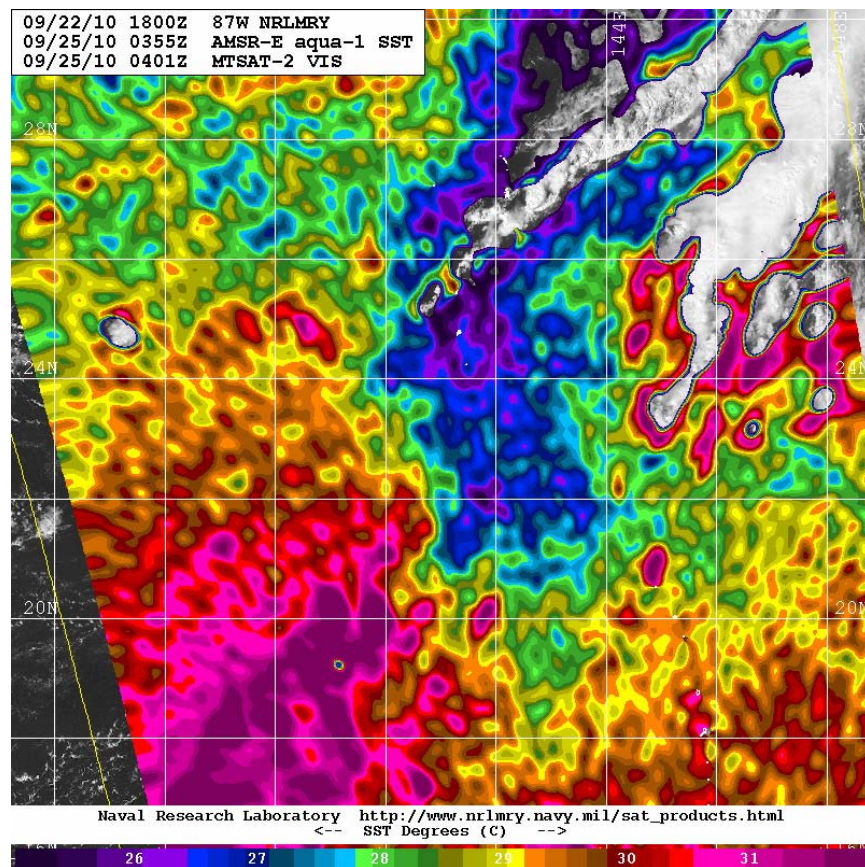


Figure 8: AMSR-E SST product created in near real-time by NRL to monitor typhoon induced upwelling. Note the cold wake as typhoon Malakis transited northward through the domain.